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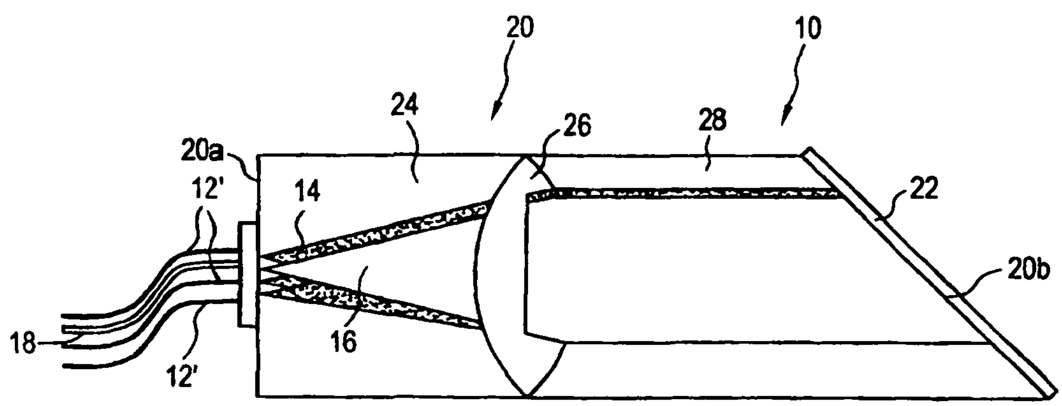

(57) Abstract

A wavelength division multiplexer is provided that integrates an axial gradient refractive index element with a diffraction grating to provide efficient coupling from a plurality of input optical sources (each delivering a single wavelength to the device) which are multiplexed to a single polychromatic beam for output to a single output optical receiver. The device comprises: (a) means for accepting optical input from at least one optical source, the means including a planar surface; (b) a coupler element comprising: (1) an axial gradient refractive index collimating lens having a planar entrance surface onto which the optical input is incident and, (2) a homogeneous index boot lens affixed to the axial gradient refractive index collimating lens and having a planar but tilted exit surface; (c) a diffraction grating, such as a Littrow diffraction grating, on the tilted surface of the homogeneous index boot lens which combines a plurality of spatially separated wavelengths from the optical light; and (d) means to output at least one multiplexed, polychromatic output beam, the means including a planar surface. The device may be operated in the forward direction as a multiplexer or in the reverse direction as a demultiplexer.

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INTEGRATED BI-DIRECTIONAL AXIAL GRADIENT REFRACTIVE INDEX/-DIFFRACTION GRATING WAVELENGTH DIVISION MULTIPLEXER

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is related to two other patent applications, the first entitled "Integrated Bi-Directional Dual Axial Gradient Refractive Index/Diffraction Grating Wavelength Division Multiplexer" [D-97031] and the second entitled "Integrated BiDirectional Gradient Refractive Index Wavelength Division Multiplexer" [D-97032], both filed on even date herewith and assigned to the same assignee. This and the two related applications are all directed to wavelength division multiplexers, and differ in the presence or absence of a diffraction grating and the number of gradient refractive index elements.

TECHNICAL FIELD

The present invention relates generally to axial gradient refractive index lenses, and, more particularly, to axial gradient refractive index lenses employed in wavelength division multiplexing applications.

BACKGROUND ART

Wavelength division multiplexing (WDM) is a rapidly emerging technology that enables a very significant increase in the aggregate volume of data that can be transmitted over optical fibers. Traditionally, most optical fibers have been used to unidirectionally carry only a single data channel at one wavelength. The basic concept of WDM is to launch and retrieve multiple data channels in and out, respectively, from an optical fiber. Each data channel is transmitted at a unique wavelength, and the wavelengths are appropriately selected such that the channels do not interfere with each other, and the optical transmission losses of the fiber are low. Today, commercial WDM systems exist that allow transmission of 2 to 32 simultaneous channels.

WDM is a cost-effective method of increasing the volume of data (commonly termed bandwidth) transferred over optical fibers. Alternate competing technologies to increasing bandwidth include the burying of additional fiber optic cable or increasing the transmission speed on optical fiber. The burying of additional fiber optic cable costs on the order of $15,000 to $40,000 per Km. Increasing the optical transmission rate is increasing limited by speed and economy of the electronics surrounding the fiber optic system. One of the primary strategies to electronically increasing bandwidth has been to use time division multiplexing (TDM), which gangs or multiplexes multiple lower rate electronic data channels together into a single very high rate channel. This technology has for the past 20 years been very effective for increasing bandwidth; however, it is now increasingly difficult to improve transmission speeds, both from a technological and economical standpoint. WDM offers the potential of both an economical and technological solution to increasing bandwidth by using many parallel channels. WDM is complimentary to TDM, that is, WDM can allow many simultaneous high transmission rate TDM channels to be passed over a single optical fiber.

The use of WDM to increase bandwidth requires two basic devices that are conceptually symmetrical. The first device is a wavelength division multiplexer. This device takes multiple beams - each with discrete wavelengths and initially spatially separated in space - and provides a means of spatially combining all of the different wavelength beams into a single polychromatic beam suitable for launching into an optical fiber. The multiplexer may be a completely passive optical device or may include electronics that control or monitor the performance of the multiplexer. The input of the multiplexer is typically accomplished with optical fibers; however, laser diodes or other optical sources may be employed. The output of the multiplexer is typically an optical fiber.

Similarly, the second device for WDM is a wavelength division demultiplexer. This device is functionally the opposite of the multiplexer; it receives a polychromatic beam input from an optical fiber and provides a means of spatially separating the wavelengths. The output of the demultiplexer is typically interfaced to optical fibers or to photodetectors.

During the past 20 years, various types of WDMs have been proposed and demonstrated; see, e.g., (1) W.J. Tomlinson, *Applied Optics*, Vol. **16**, No. **8**, pp. 2180-2194 (Aug. 1977); (2) A.C. Livanos et al, *Applied Physics Letters*, Vol. **30**, No. 10, pp. 519-521 (15 May 1977); (3) H. Ishio et al, *Journal of Lightwave Technology*, Vol. **2**, No. 4, pp. 448-463 (Aug. 1984); (4) H. Obara et al, *Electronics Letters*, Vol. **28**, No. 13, pp. 1268-1270 (18 June 1992); (5) A.E. Willner et al, *IEEE Photonics Technology Letters*, Vol. **5**, No. 7, pp. 838-841 (July 1993); and (6) Y.T. Huang et al, *Optics Letters*, Vol. **17**, No. 22, pp. 1629-1631 (15 Nov. 1992).

However, despite all of the above approaches, designs, and technologies, there remains a real need for a WDM device which possesses all the characteristics of. low cost, component integration, environment and thermal stability, low channel crosstalk, low channel signal loss, ease of interfacing, large number of channels, and narrow channel spacing.

DISCLOSURE OF INVENTION

In accordance with the present invention, a wavelength division multiplexer or demultiplexer combines an axial gradient refractive index element with a diffraction grating to provide an integrated, bi-directional wavelength division multiplexer or demultiplexer device. For simplicity, the multiplexer function will be extensively discussed; however, such discussions of the invention will also be directly applicable to the demultiplexer due to the symmetry of the multiplexer and demultiplexer function. The multiplexer device of the present invention comprises:

(a) a means for accepting a plurality of optical input beams containing at least one wavelength from optical fibers or other optical sources such as lasers or laser diodes, the means including a planar front surface onto which the optical input light is incident and suitable for the connection of input optical fibers or integration of other devices;

(b) a coupler subsystem comprising (1) an axial gradient refractive index collimating lens operative associated with the planar front surface and (2) a homogeneous index boot lens affixed to the axial gradient refractive index collimating lens and having a planar but tilted back surface;

(c) a near-Littrow diffraction grating operatively associated with the homogeneous index boot lens, formed or affixed at the planar exit surface of the coupler subsystem which combines a plurality of spatially separated wavelengths into at least a single polychromatic optical light beam and reflects the combined optical beam back into the coupler subsystem at essentially the same angle as the incident beams;

(d) an optional array of electrooptical elements for refracting the plurality of wavelengths to provide channel routing or switching capabilities; and

(e) a means of outputting at least one multiplexed, polychromatic output beam for at least one optical fiber, said means being located at the same input surface in (a).

The device of the present invention may be operated in either the forward direction to provide a multiplexer function or in the reverse direction to provide a demultiplexer function.

Further, the device of the present invention is inherently fully bi-directional and can be used simultaneously as a multiplexer and demultiplexer for applications such as network hubs or intersections that distribute channels to various areas of a network. The axial gradient refractive index and diffraction grating-based WDM devices of the present invention are unique because they contain one or more homogeneous index boot lenses which allows integration of all the optical components into a single integrated device. This greatly increases the. ruggedness, environmental and thermal stability while simultaneously avoiding the introduction of air spaces which cause increased alignment sensitivity, device packaging complexity, and cost.

Additionally, the homogeneous index boot lenses provide large, planar surfaces for device assembly, alignment and the integration of additional device functions. The use of an axial gradient refractive index lens allows very high performance imaging from a lens with traditional spherical surfaces, thereby providing the diffraction-limited optical imaging necessary for WDM applications. Further, axial gradient refractive index lenses are formed with high quality and low cost. Alternately, aspheric shaped lenses could be used in place of axial gradient refractive index lenses; however, the collimating performance is the same, but it is exceedingly difficult to

create a one-piece, integrated device with aspheric surfaces. Further, aspherical lenses are typically very costly and suffer from ghosting-types of reflections which are very undesirable.

The integration of the WDM device allows for a compact, robust, and environmentally and thermally stable system. In particular, integration of the components into a solid block maintains component alignment, which provides long-term performance in contrast to non-integrated air-spaced devices that characteristically degrade in alignment and therefore performance over time.

Overall, the present invention features a novel approach to WDM. The use of optical lenses in conjunction with a diffraction grating allows all wavelengths to be multiplexed simultaneously and treated uniformly. This is contrast to the less desirable serial WDM approaches that use interference filter-based or fiber Bragg gratings. Such serial WDM approaches suffer from significant optical loss, crosstalk, alignment, and temperature issues. Further, compared to other parallel multiplexing approaches such as array waveguide grating devices, fused fiber couplers, or tree waveguide couplers, the present invention performs the wavelength separation freely inside glass as opposed to inside of lossy waveguiding structures. Thus, the present invention has the distinct advantages of lower optical signal loss through the device and ease of assembly and alignment compared to the current art.

Other objects, features, and advantages of the present invention will become apparent upon consideration of the following detailed descriptions and accompanying drawings, in which like reference designations represent like features throughout the FIGURES. It will be apparent to one skilled in the art that additional objects, features, and advantages not expressly discussed here are inherent to and follow from the spirit of this invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings referred to in this description should be understood as not being drawn to scale except if specifically noted.

FIG. 1 is a side elevational schematic view (FIG. 1a) and a top plan schematic view (FIG. lb) of a wavelength division multiplexer device of the present invention,

with an axial gradient refractive index lens, near-Littrow diffraction grating, and multiple optical fiber inputs multiplexed to one optical fiber output;

FIG. 2a is a perspective view of a portion of the device of FIG. 1, illustrating in detail the input and output optical connections to the device;

FIG. 2b is a perspective view of the input portion of the device of FIG. 1, illustrating an alternate input configuration in which the input is an array of laser diodes;

FIG. 2c is a perspective view of a portion of the device of FIG. 1, illustrating an alternate output configuration for a demultiplexer device in which the output is an array of photodetectors;

FIG. 3 is a side elevational schematic view (FIG. 3a) and a top plan schematic view (FIG. 3b) similar to the device of FIG. 1, but omitting a homogeneous index boot lens element between the input and the axial gradient refractive index collimating lens;

FIG. 4 is a perspective view of a portion of the device of FIG. 1, but including an array of electrooptical beamsteering elements (parallel to the grating direction) to individually beamsteer each input channel to an output fiber port;

FIGS. 5a-5c are plots on coordinates of intensity and wavelength, depicting different intensity profiles for different configurations or of the multiplexer of the present invention;

FIG. 6 is a perspective view of a portion of the device of FIG. 1, similar to that of FIG. 2a, but including an array of electrooptical beamsteering elements (perpendicular to the grating direction) to individually beamsteer each input channel to an output fiber port;

FIG. 7 is a perspective view of a portion of the device of FIG. 1, similar to that of FIG. 2a, but including an electrooptical beamsteering element to individually beamsteer each input channel to an output fiber port; and

FIG. 8 is a perspective view of a portion of the device of FIG. 1, but employing two multiplexers to perform a channel blocking function by incorporating an electrooptical blocking array on the input face of one multiplexer.

BEST MODES FOR CARRYING OUT THE INVENTION

Reference is now made in detail to specific embodiments of the present invention, which illustrate the best modes presently contemplated by the inventors for practicing the invention. Alternative embodiments are also briefly described as applicable.

FIG. 1 depicts two views of a preferred embodiment of the present invention, which embodies an axial gradient refractive index/diffraction grating wavelength division multiplexer device. Specifically, FIG. la illustrates the side elevational view of the device, while FIG. lb illustrates the top plan view.

The device **10** of the first embodiment takes an input fiber array **12** of N discrete wavelengths of light **14** and spatially combines them into a single optical beam 16 and outputs the single beam to a single optical fiber output **18**. Each wavelength is transmitting information superimposed on it by other means, which are not shown here and which do not form a part of this invention, but are well known in this art.

The device **10** further comprises a coupler element **20**; on the exit surface **20b** of the coupler element is formed or placed a near-Littrow diffraction grating **22**. The near-Littrow diffraction grating **22** provides both the function of angularly dispersing optical beams of differing wavelength and reflecting the optical beams back at very nearly the same angle as the incident angle.

In the present invention, the diffraction grating **22** is used to provide angular dispersion, the amount of which depends upon the wavelength of each incident optical beam. Further, the diffraction grating **22** is oriented at a special angle relative to the optical axis of the device **10** in order to obtain the Littrow diffraction condition for one wavelength that lies within or near the wavelength range for the plurality of optical beams present. The Littrow diffraction condition requires that a light beam be incident on and reflected back from the grating at the same exact angle. Therefore, it will be readily apparent to one skilled in the art that a near-Littrow diffraction grating is used to obtain near-Littrow diffraction for each of the plurality of wavelengths present.

The Littrow diffraction angle is determined by the well-known formula

$m\lambda = d (\sin (\alpha_i)$

where m is the diffraction order, λ is the wavelength, d is the diffraction grating groove spacing, and α_i is the same incident and diffracted angle. It will be readily apparent to one skilled in the art that the diffraction grating angle depends upon numerous variables, which may be varied as necessary to optimize the performance of the device. For example, variables affecting the grating diffraction angle include the desired grating diffraction order, grating blaze angle, number of channels, spatial separation of channels, and wavelength range of the device.

The coupler element **20** comprises a first homogeneous index boot lens **24** joined or affixed to an axial gradient refractive index collimating lens **26**. The axial gradient refractive index lens in turn is joined or affixed to a second homogeneous index boot lens **28**. The joining or affixing is accomplished using optical cement or other optically transparent bonding technique. In this first embodiment, the array **12** of optical fibers **12'** are positioned so that light emanating from the end the optical fibers is incident on the entrance surface **20a** of the coupler element **20**. Each fiber **12'** provides light beams of discrete wavelengths.

FIG. 2a depicts the details of coupling the input fiber array **12** into the coupler **20** and launching a plurality of optical beams **14** therein, one for each fiber **12'**, using a suitable coupler/interconnect **30**. Similarly, the combined optical beam **16** is coupled into the single fiber output **18** by a suitable coupler interconnect **32**. Such couplers/interconnects **30, 32** are well known in the art and do not form a part of this invention.

The plurality of spatially separated light beams **14** enters the first homogeneous index boot lens **24**, where they are expanded in diameter. Subsequently, the plurality of light beams **14** enters the first axial gradient refractive index lens **26**, where they are collimated and then pass through the second homogeneous index boot lens **28**. At the exit surface **20b** of the second homogeneous index boot lens **28**, the collimated light beams are reflected by the near-Littrow diffraction grating **22**, which removes the angular separation within the plurality of light beams **14** and creates a single light beam **16** containing within itself a plurality of wavelengths. The single light beam **16** passes back through the coupling element **20** in the reverse direction (first, through the

second homogeneous index boot lens **28**, then through the axial gradient refractive index focusing lens **26**, and finally the first homogeneous index boot lens **24**). The single focused beam **16** is then incident on an optical fiber **18**, attached at the entrance surface **20a** of the first homogeneous index boot lens **24** of the coupler element **20**.

In the second homogeneous index boot lens **28**, the exit surface **20b** is formed with a beveled edge at the same angle as the Littrow diffraction angle given by the equation above. The bevel angle is about an axis parallel to the axis of the diffraction grating **28**.

The diffraction grating **22** is formed on the far surface **20b** of the coupler element **20**. It may be formed by a variety of techniques, such as a three-dimensional hologram in a polymer medium, which can be attached to the exit surface **20b**, such as with an optical cement. Alternatively, the diffraction grating **22** may be ruled on the exit surface **20b** by a mechanical ruling engine or by other techniques or technologies well-known in this art. The ruled diffraction grating **22** could be formed directly on the exit surface **20b** or formed in a separate planar material such as polymer, glass, silicon, etc., that is secured to the end of the coupler element **20**, again, by an optical cement.

In order to prevent the multiplexed output beam **16** (a polychromatic beam) from being reflected directly back into the array of input beams, the input array and output fiber are symmetrically separated slightly apart from the central axis of the lens. Alternatively, a small (generally less than 3°) tilt is created in the second homogeneous index boot lens **28**. This small tilt is made by rotating the back surface of the second homogeneous boot lens **28** about an axis that lies perpendicular to the ruling direction of the diffraction grating **22**. This tilt spatially separates the output **18** and input array **12** for efficiency and ease of coupling in and out of the device **10**. In the embodiment depicted in FIG. 1, the plurality of optical fibers **12'** comprising the input array **12** and the optical fiber output **18** are shown in FIG. 2a. Again, due to the tilt in the second homogeneous index boot lens **28**, the plurality of optical inputs **12'** and the optical output **18** are slightly spatially separated at the first surface **20a** of the first homogeneous index boot lens **24**.

In the embodiment depicted in FIG. 1, a plurality of laser diodes **34**, shown in FIG. 2b, may be used in place of the plurality of optical fibers **12'** to provide optical beam inputs **14** for the wavelength division multiplexer **10**. The array of laser diodes **34** may either be butt-coupled to the WDM device **10**, may be longitudinally separated, or may have appropriate focusing lenses placed between the output face and the laser diode array to provide the best coupling and the lowest amount of signal loss or crosstalk.

In the second embodiment, the device **10** shown in FIG. 1, as with all of the devices described herein, may be operated in the converse configuration, with a single optical fiber input **18** that introduces a single polychromatic light beam **16** carrying multiple discrete wavelength channels. The channels are spatially separated by the demultiplexing function of the device **10** for output to a plurality of optical fibers **12'**.Each output fiber **12'** carries only a single and discrete wavelength channel. Functionally, in this embodiment, the demultiplexer provides an identical but opposite function to the multiplexer device **10** described in FIG. 1. In the demultiplexer embodiment, a plurality of photodetectors **36** shown in FIG. 2c, may be used in place of a plurality of optical fibers **12'** to provide optical beam outputs for the wavelength division demultiplexer. The array of photodetectors **36** may either be butt-coupled to the WDM device **10**, may be longitudinally separated, or may have appropriate focusing lenses placed between the output face and photodetector array to provide the lowest amount of signal loss or crosstalk.

In a third embodiment, depicted in the two views of FIG. 3, the first homogeneous index boot lens **24** is removed to create a more compact device or for devices where the use of the first homogeneous index boot lens is not necessary for performance. FIG. 3a depicts the side elevational view of the device, while FIG. 3b depicts the top plan view. In this embodiment, the axial gradient refractive index lens **26'** possesses a planar exit face **20a** for directly connecting to the plurality of inputs **12'** and the single output fiber **18**. An alternate implementation (not shown) of this third embodiment would be to incorporate an air space between the input plurality of optical fibers **12'** or laser diodes **34** and the axial gradient refractive index lens **26'**. The introduction of air space is not a preferred embodiment, as it increases the

complexity of assembly and alignment of the multiplexer device **10** and would be subject to greater environmental and temperature instability versus the integrated block approach of the preferred embodiments of the present invention. All elements of this third embodiment are joined or affixed using optical cement or other optically transparent bonding technique.

In a fourth embodiment, shown in FIG. 4, an array of non-linear electrooptic elements **38** is integrated to provide a capability for selectively routing the multiplexed light **16** into one of several possible colinear fiber outputs **18a, 18b, 18c, 18d, 18e**. This is exceedingly valuable for optical networking, whereas the wavelength division multiplexer device **10** can provide simultaneous integrated multiplexing and routing functions. The electrooptic element array **38** is an electrically controlled solid-state optical material in which the refractive index can be modified by varying the electrical current applied to the material. Such electrooptic elements are well-known in the art; examples include lithium niobate, and certain polymer materials.

The output array **18** is separated from the surface **20a** by an optional spacer or blank **40**. The blank **40** merely provides the same spacing as the beamsteering array **38** to enable ease of input and output coupling.

The change in refractive index is used to increase or decrease the angle of light propagation (relative to the gradient direction of the electrooptical material). It is very desirable to use electrooptical elements to independently shift the position of the light beams **14** to an arbitrary output fiber port **18**. The shift direction is parallel to the input **12'** and output arrays **18**. As shown in FIG. 4, the array of electrooptical elements **38** are is used to direct the output to one of a plurality of possible fiber outputs **18a, 18b, 18c, 18d, 18e**. The plurality of output optical fibers **18a-18e** is collinear. It will be appreciated that while five such output optical fibers are shown, the invention is not so limited, and any reasonable number of output optical fibers may be employed in the practice of the invention.

An alternate fifth embodiment would use the device in the same direction as a demultiplexing and routing device, in which each fiber **12'** inputs a plurality of wavelengths that are demultiplexed and beamsteered to the output fiber array **18**. The preferred orientation of the electrooptical element **38** is such that the spatial variation

at the output face **20a** of the device **10** is in a direction parallel to input array **12** and output array **18**. In this alternate embodiment, the demultiplexed outputs **16** may be routed to one of many possible output arrays of fibers **18** as shown in FIG. 4. Alternately, the demultiplexed outputs may be routed to one of many possible arrays of photodetectors (not shown), as discussed above in connection with FIG. 2c.

In the sixth embodiment, the device of FIG. 1 may be specially designed and constructed such that individual wavelength channels in the polychromatic output beam are unevenly focused at the output face of the multiplexer. As graphically shown in FIG. 5a, the preferential embodiment of the device of FIG. 1 creates a very uniform plurality of focused beams that have uniform intensity distributions. However, the current embodiment alters the design (such as lens curvature or axial gradient refractive index profile) of the collimating lens assembly in order to incorporate a variation in intensity distributions as a function of increasing wavelength, such as shown in FIGS. 5b and 5c. These variations need not be linear but may be fairly complex and non-linear to match the non-uniform gain profiles of optical amplifiers, laser diode arrays, or other devices in an optical network.

In the seventh embodiment, shown in FIG. 6, the wavelength division multiplexing device **10** of FIG. 1 is used to create a 4 x 4 switch and multiplexer. The basic device **10** of FIG. 1 is used to combine and/or route a plurality of wavelengths that are present at the input face **20a** of the device. Integrated to the input face **20a** is first an array of electrooptical beamsteering elements **42**, each element being individually addressable (one element for each wavelength) and capable of directing light in a direction perpendicular to the input array **12**. Each element **40** is used to direct the light from a single channel **12'** to an arbitrary output port **18a, 18b, 18c, 18d**. The blank **40** merely provides the same spacing as the beamsteering array **42**, as in FIG. 4, to enable ease of input and output coupling.

In the eighth embodiment, shown in FIG. 7, the wavelength division multiplexing device **10** of FIG. 1 is used to create a 1 x 4 switch and demultiplexer. The basic device **10** of FIG. 1 is used to both separate and route a plurality of wavelengths on input fiber **18** that are present at the input face of the device **20a**. Integrated to the input face **20a** is first an electrooptical beamsteering element **44**

capable of directing light in a direction parallel to ruling direction of the diffraction grating **22** (not shown in FIG. 7). The beamsteering element **44** is used to direct the light of a single wavelength to one of two demultiplexed output ports **12a, 12b**. The blanks **40** merely provide the same spacing as the beamsteering array **44**, as in FIGS. 4 and 6, to enable ease of input and output coupling.

In the ninth embodiment, shown in FIG. 8, the wavelength division multiplexing device **10** of FIG. 1 is used to create a 4-wavelength blocking switch **110** by using two multiplexing devices **10a, 10b** and an array of electrooptical blocking elements **46.** The input and output of the blocking switch device **110** is a single fiber **18** at each. This device provides a blocking function fcr each individual wavelength.

Attached to the output face **20a** of the first multiplexer device **10a** is first an array **46** of electrooptical blocking elements that are individually addressable (one element for each wavelength), which selectively block or unblock the passage of light. The array of blocking elements **46** are formed from a liquid crystal, electrochromic solid-state material, or other similar material in which the amount of transmission can be varied as a function of the power applied to the individual array element.

After the blocking array is located either Porro-type reflective prisms (not shown) or fiber loops **48** which take the individual outputs and reroute them to separate positions on the input face **20a** of the adjacent multiplexer device **10b**. The inputs then pass through the second device **10b**, are multiplexed for output to a single fiber **18** on the output face **20a** of the second device. The blank **40** merely provides the same spacing as the beamsteering array **46**, as above, to enable ease of input and output coupling.

An alternate embodiment of the present device would be to use the blocking elements **46** to tailor the amount of optical energy (gain) transmitted on each wavelength. Thus, this blocking switch **110** can be used to flatten the uneven gain from other portions of the optical network by devices such as optical amplifiers, laser diode arrays, or the network in general. Examples of possible changes in the gain profile are shown in FIGS. 5a, 5b, and 5c, discussed above.

INDUSTRIAL APPLICABILITY

The integrated axial gradient refractive index/diffractive wavelength division multiplexer/demultiplexer of the present invention is expected to find broad application in WDM-based network and communication systems.

Thus, there has been disclosed an integrated axial gradient refractive index/diffraction grating wavelength division multiplexer and demultiplexer. It will be readily apparent to those skilled in this are that various changes and modifications of an obvious nature may be made, and all such changes and modifications are considered to fall within the scope of the present invention, as defined by the appended claims.

WHAT IS CLAIMED IS:

1. An integrated axial gradient refractive index/diffraction grating wavelength division multiplexer device comprising:

(a) a means for accepting at least one optical input beam containing at least one wavelength from an optical source, said means including a planar front surface onto which said optical input light is incident and suitable for connection of both input and output optical devices;

(b) a coupler subsystem comprising (1) an axial gradient refractive index collimating lens operatively associated with said planar front surface and (2) a homogeneous index boot lens affixed to said first axial gradient refractive index collimating lens and having a planar exit surface from which said at least one optical beam exits and enters;

(c) a diffraction grating formed at said planar exit surface of said first coupler optical subsystem which combines a plurality of spatially separated wavelengths into at least one optical beam and reflects said at least one combined optical beam back into said coupler subsystem; and

(d) a means for producing at least one multiplexed, polychromatic output beam to an optical receiver, said means including said planar input/output surface.

2. The device of Claim 1 wherein said diffraction grating is a Littrow diffraction grating.

3. The device of Claim 1 wherein said planar exit surface is provided with a beveled surface at an angle that is normal to at least one wavelength diffracted by said diffraction grating, said beveled surface being angled so that incident wavelengths from the coupler subsystem are reflected back into the coupler subsystem,

4. The device of Claim 1 further including at least one electrooptical element for refracting either an individual or a plurality of wavelengths to provide channel routing capabilities.

5. The device of Claim 4 further comprising a non-linear electrooptical element between said input optical device and said planar front surface.

6. The device of Claim 4 further comprising an array of individually addressable electrooptical elements between said input optical device and said planar front surface.

7. The device of Claim 1 wherein said input optical device -is selected from the group consisting of optical fibers, lasers, and laser diodes.

8. The device of Claim 7 wherein said input optical device comprises at least one optical fiber transmitting a plurality of wavelengths.

9. The device of Claim 7 wherein said input optical device comprises a one dimensional array of optical fibers.

10. The device of Claim 7 wherein said input optical device comprises a two dimensional array of optical fibers.

11. The device of Claim 7 wherein said input optical device comprises a one dimensional array of laser diodes.

12. The device of Claim 7 wherein said input optical device comprises a two dimensional array of laser diodes.

13. The device of Claim 1 wherein said output optical device is selected from the group consisting of optical fibers and photodetectors.

14. The device of Claim 13 wherein said output optical device comprises a one-dimensional array of optical fibers.

15. The device of Claim 13 wherein said output optical device comprises a two-dimensional array of optical fibers,

16. The device of Claim 13 wherein said output optical device comprises a one-dimensional array of photodetectors.

17. The device of Claim 13 wherein said output optical device comprises a two-dimensional array of photodetectors.

18. The device of Claim 1 wherein said at least one optical beam is incident on said coupler subsystem and exits from said coupler subsystem, thereby acting as a multiplexer.

19. The device of Claim 18 wherein more than one said optical beam is incident on said coupler subsystem and exits from said coupler subsystem as a combined single optical beam.

20. The device of Claim 1 wherein said at least one optical beam is incident on said coupler subsystem and exits from said coupler subsystem, thereby acting as a demultiplexer.

21. The device of Claim 20 wherein at least one said optical beam is incident on said coupler subsystem and exits from said coupler subsystem as a plurality of spatially separated optical beams.

22. The device of Claim 1 further comprising at least one homogeneous index element between said input means and said coupler subsystem.

23. The device of Claim I further including at least one electrooptical element for blocking either an individual or a plurality of wavelengths to provide channel blocking capabilities.

24. The device of Claim I wherein said coupler subsystem provides a specifically desired function for channel output intensity as a function of wavelength.

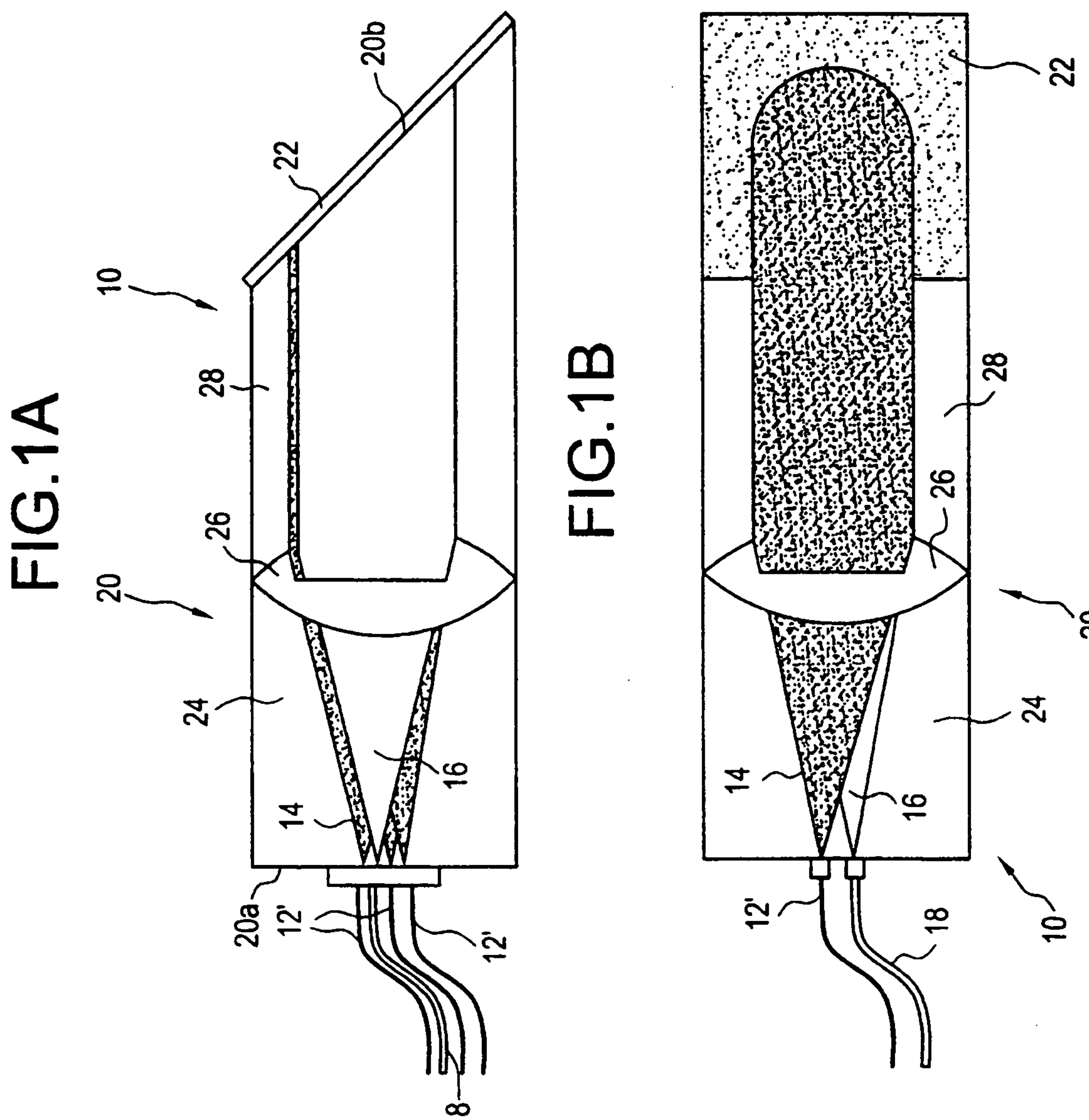


FIG.1A

FIG.1B

FIG.2A

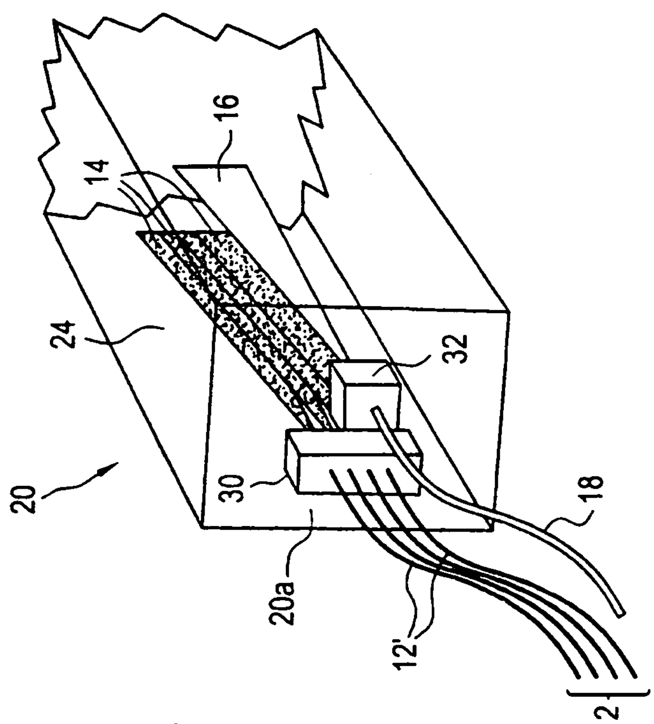


FIG.2B

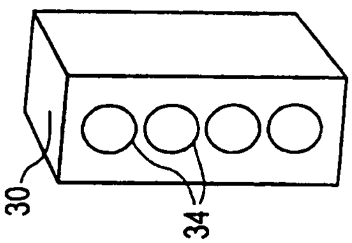
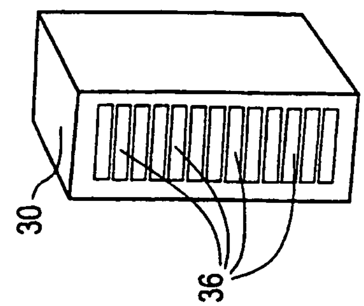


FIG.2C



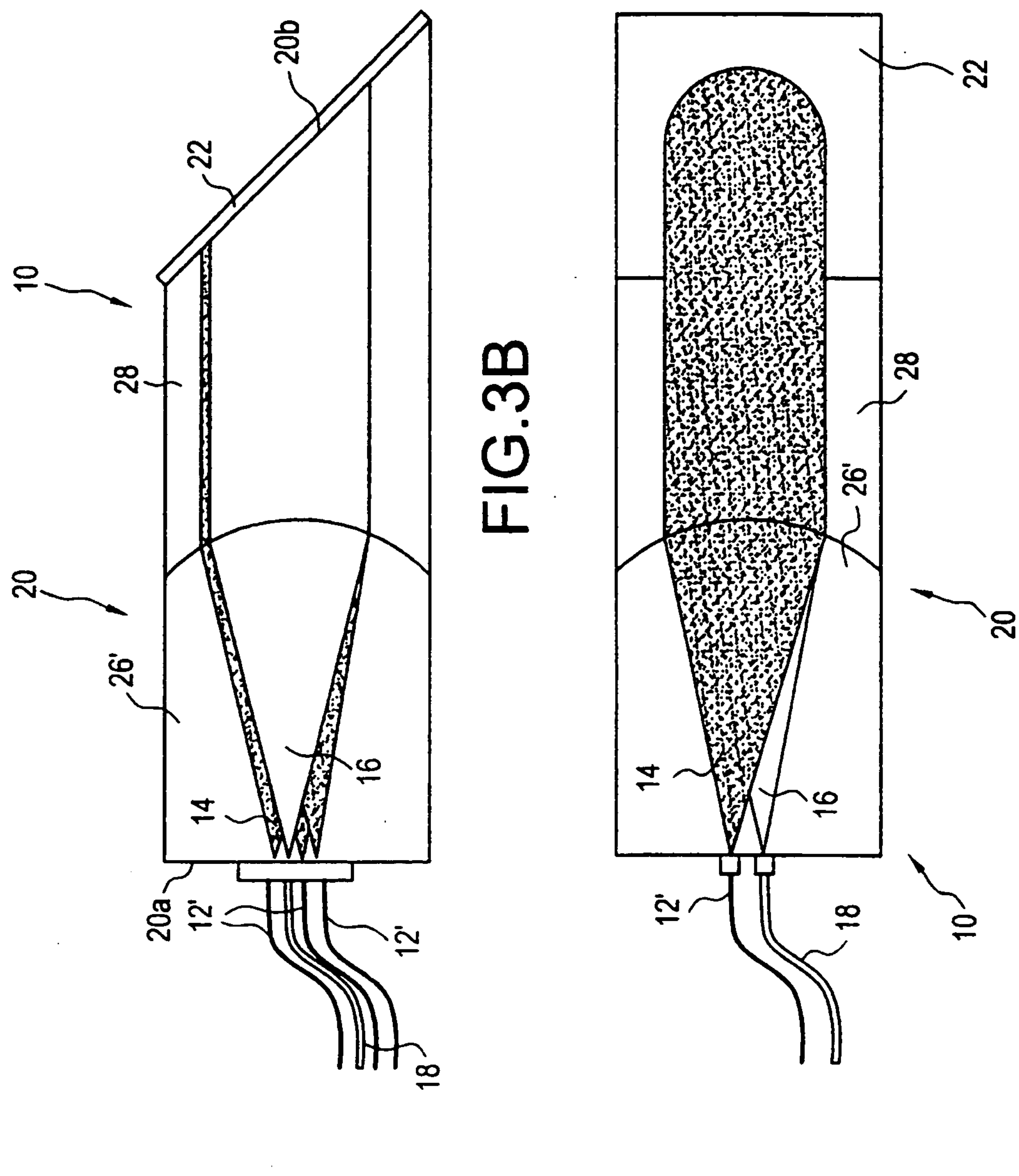


FIG.3A

FIG.3B

FIG.4

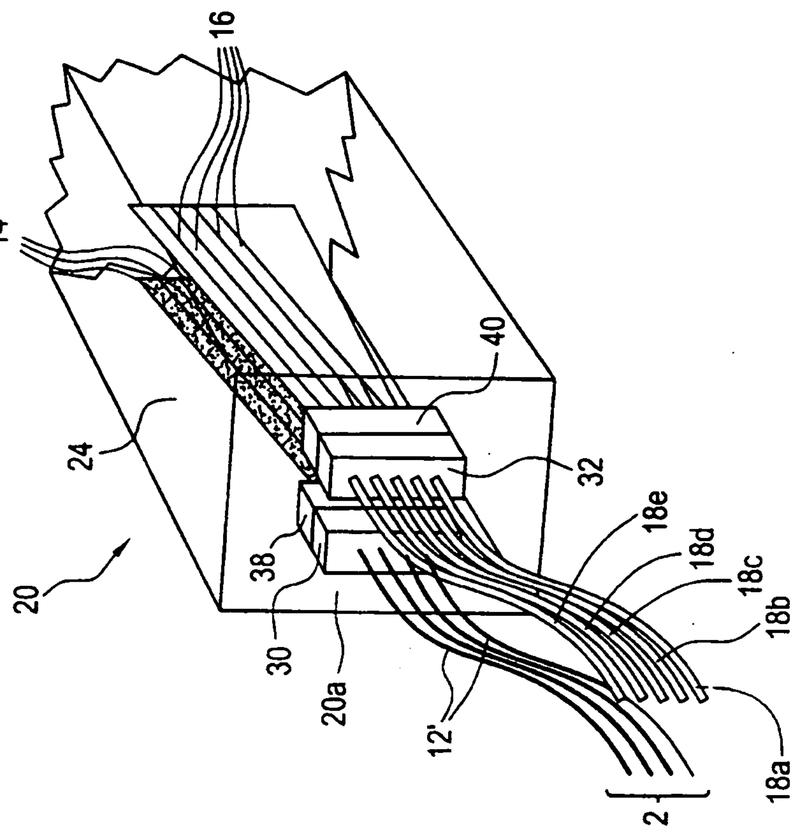


FIG.5A

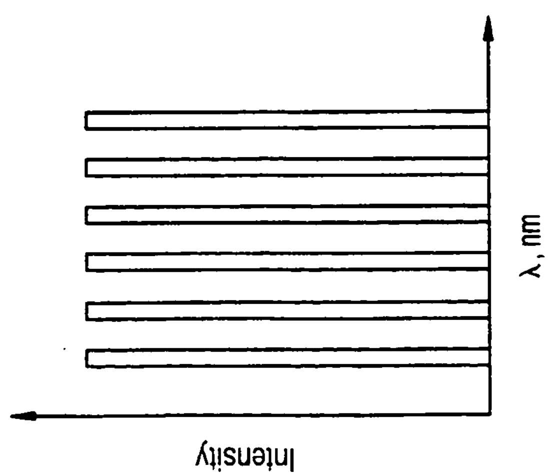


FIG.5B

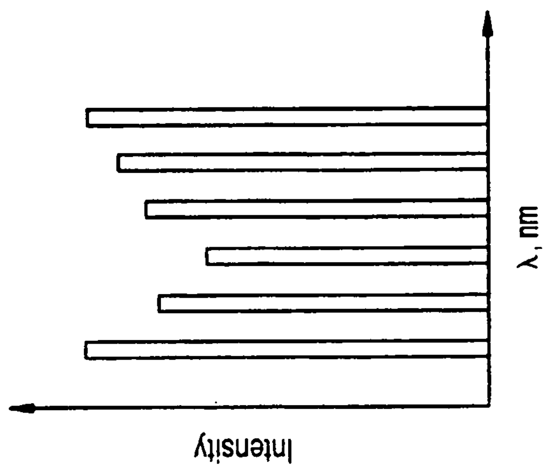


FIG.5C

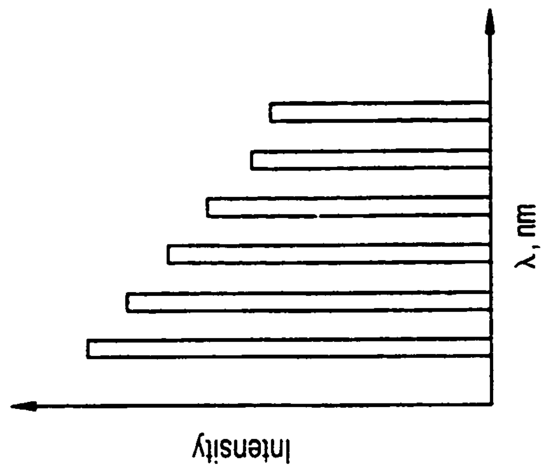


FIG.6

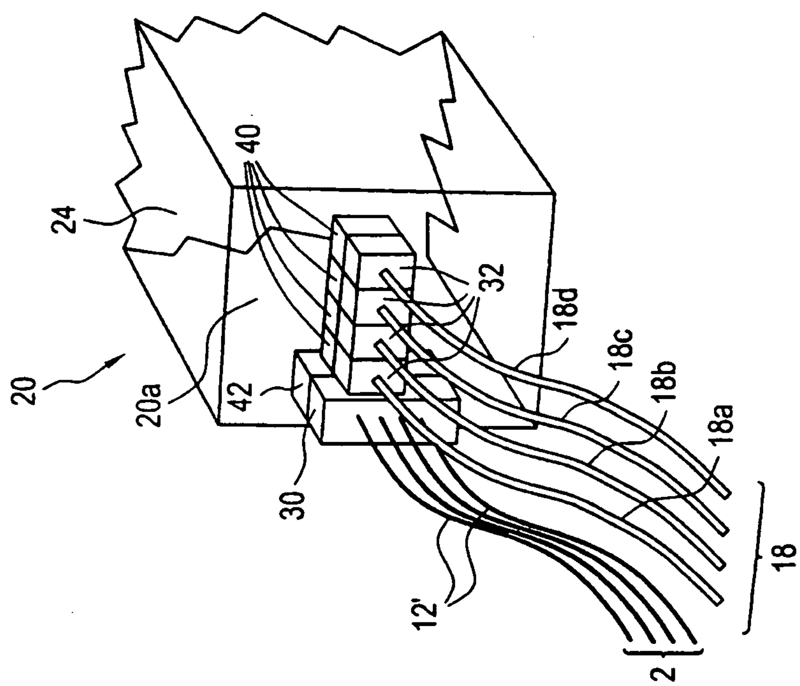


FIG.7

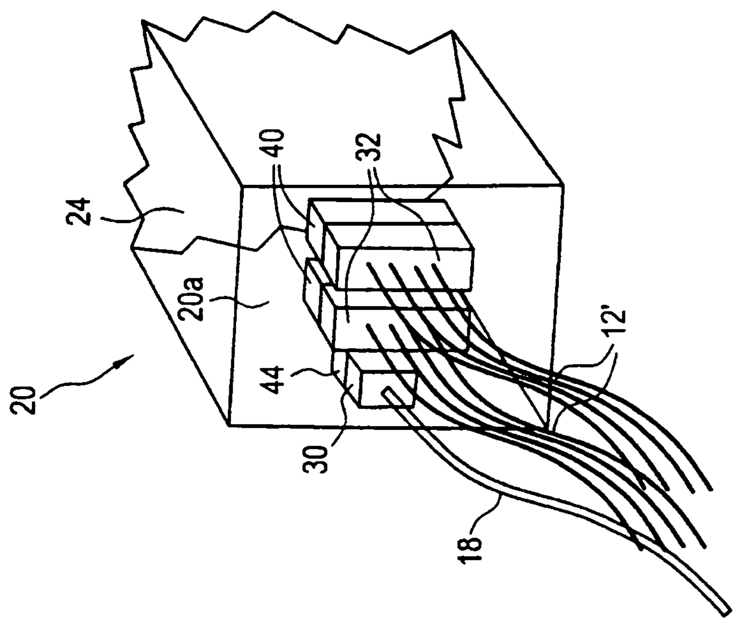
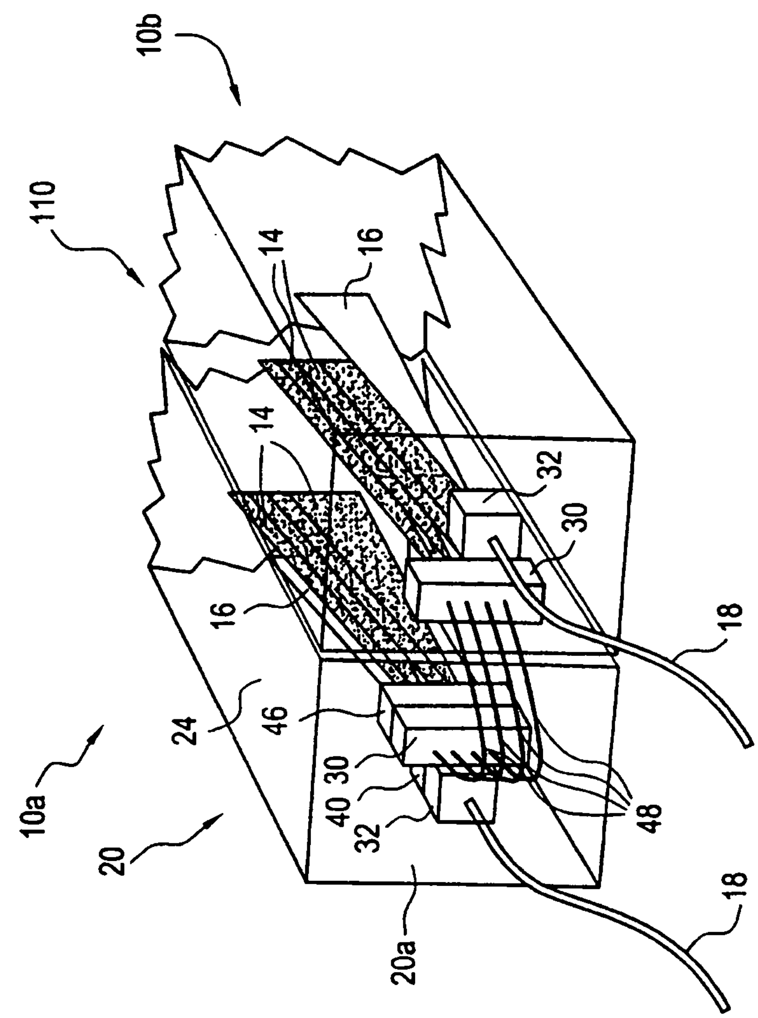


FIG.8



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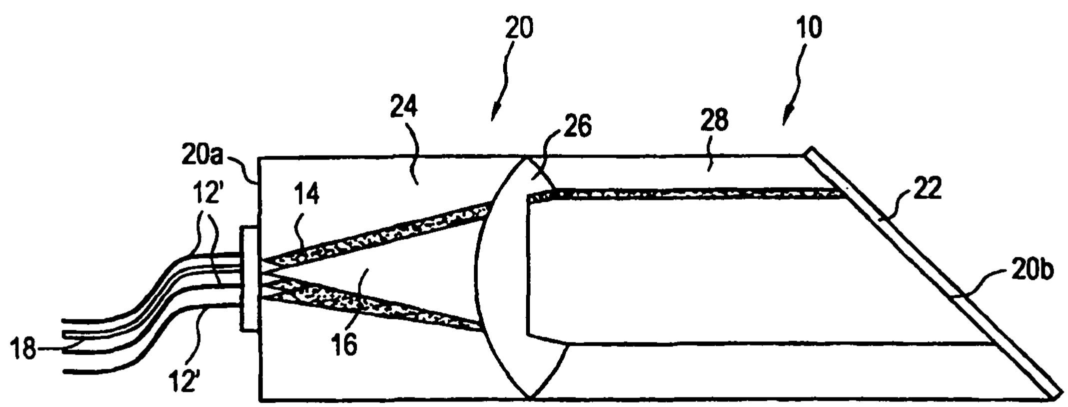

(57) Abstract

A wavelength division multiplexer that integrates an axial gradient refractive index element with a diffraction grating to provide coupling from a plurality of input optical sources (each delivering a single wavelength) which are multiplexed to a single polychromatic beam for output to a single output optical receiver. The device comprises means for accepting optical input from at least one optical source, the means including a planar surface (20a); a coupler element (20) comprising an axial gradient refractive index collimating lens (26) having a planar entrance surface onto which the optical input is incident and a homogeneous index boot lens (24, 28) affixed to the axial gradient refractive index collimating lens and having a planar but tilted exit surface (20b); a diffraction grating (22) on the tilted surface of the homogeneous index boot lens which combines a plurality of spatially separated wavelengths from the optical light; and means to output at least one multiplexed, polychromatic output beam, the means including a planar surface (20a). The device may be operated in the forward or reverse direction as a multiplexer or demultiplexer.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/26368

A. CLASSIFICATION OF SUBJECT MATTER
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US CL : 385/24
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 385/24, 33, 34, 37, 14, 49, 39; 372/50; 359/130, 131

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,355,237 (Lang et al.) 11 Oct 1994 (11-10-94), all pages	1, 2, 7-21
A	US 5,228,103 (Chen et al.) 13 Jul 1993 (13-07-93), all pages	1-2, 4, 7-21, 23
A	US 5,371,813 (Artigue) 06 Dec 1994 (06-12-94), all pages	1-2, 4, 7-21, 23
A	US 5,119,454 (McMahon) 02 Jun 1992 (02-01-92), all pages	1-3, 7-22
A	US 5,835,517 (Jayaraman et al.) 10 Nov 1998 (10-11-98), all pages	1-2, 4, 7-23

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Electronic data bases consulted (Name of data base and where practicable terms used):

U.S. PTOAPS

search terms: optic?(2a)fib?, wavelength?(2a)div?(2a)(multi-plex? or multiplex?), WDM